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**OVERLEAF: Earth—The Quintessential
Terrestrial Body**

Although the Earth is not explicitly discussed in this report, all knowledge of other bodies within the solar system ultimately reflects perspectives gained through experiences in our own world. Things we know about the Earth influence our perception of other planets, and knowledge gained through the study of the other members of our solar system can affect our perception and beliefs about Earth.

(Apollo 17 photograph 17-148-22727, showing the antarctic icecap, most of Africa and Arabia)

JPL PUBLICATION 77-51, VOLUME I

Report of the Terrestrial Bodies Science Working Group

Volume I. Executive Summary

September 15, 1977

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
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PREFACE

The Terrestrial Bodies Science Working Group (TBSWG) was chartered in the spring of 1976 by the National Aeronautics and Space Administration's Lunar and Planetary Program Office "to develop general plans for the exploration of the terrestrial bodies of the solar system, including the satellites and the asteroids, and for the scientific understanding of data acquired during this exploration, both from mission operations and from studies not directly related to missions." The group has reviewed current knowledge of the terrestrial bodies, current NASA-sponsored programs and research, and available mission concepts and studies. In order to concentrate its efforts within definable limits, the group limited its consideration to the following objects: Mercury, Venus, the Moon, Mars, Asteroids, Galilean satellites, and comets. Earth, the most studied terrestrial planet, was considered a special case, important but beyond the scope of this study.

The results of the study are documented in this 9-volume report. Principal recommendations and conclusions are contained in Volume I (Executive Summary); reports and working papers of the study subgroups are presented in Volumes II-IX.

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ABSTRACT

In this report the Terrestrial Bodies Science Working Group reviews current knowledge of Mercury, Venus, the Moon, Mars, asteroids, Galilean satellites, and comets, together with related NASA-sponsored programs and available mission concepts and studies. Exploration plans for the period 1980-1990 are presented.

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SECTION I

INTRODUCTION

The initiation of solar system exploration with spacecraft is one of the most significant scientific milestones in the history of mankind. In the first two decades of this exploration, close-up observations of Mercury, Venus, Mars, Jupiter and the Moon have been made and our understanding of the solar system has been revolutionized. During a relatively short period of time, studies of planets have advanced from those made by Earth-based telescopes to detailed in situ scientific measurements on the surfaces of other planets. Each planetary mission has provided new knowledge for a better understanding of the nature and history of objects in the solar system.

A remarkable and complex picture of the planets and their satellites is beginning to emerge from planetary observations. For example, Venus has a very dense and hot atmosphere, whereas Mars has a very rarefied atmosphere. In both cases, carbon dioxide (CO₂) is the major constituent of the atmosphere, instead of nitrogen as in the case of the Earth. The Galilean satellite Io has an atmosphere of ionized sodium. Mars has giant volcanoes larger than any on Earth, while the Moon has large basalt-filled maria. Yet neither Mercury, Mars nor the Moon have developed plate tectonic features such as appear on the Earth. Meteorite impacts seem to have played a universal role in shaping the surfaces of the terrestrial planets and satellites, particularly early in their histories.

A number of highly successful missions have provided us with a first look at several planets. The Moon and Mars have been explored quite intensively by the Apollo and Viking missions. Before 1980, the Pioneer Venus mission will provide a more detailed model of Venus's atmosphere and some information on its topography. The Mariner Jupiter/Saturn (Voyager) mission will give partial imagery of some Galilean satellites. Comets and asteroids, on the other hand, have not yet been explored by spacecraft.

We are now at a major decision point in planetary exploration: initial observations have been made and the next phase of planetary exploration requires new commitment and resources. This is a logical time to take stock of what data we have, evaluate our present knowledge, elucidate science objectives, and develop a rational program for exploring the terrestrial bodies of the solar system during the period 1980-1990. In this report the Terrestrial Bodies Science Working Group (TBSWG) presents such a program for Mercury, Venus, Moon, Mars, the asteroids, Galilean satellites, and comets. In the following sections science objectives, exploration strategy, mission recommendations, and nonmission program recommendations pertaining to the required SR&T developments, data analysis and synthesis, and other factors are described.

SECTION II

SCIENCE OBJECTIVES AND GOALS FOR EXPLORATION
OF TERRESTRIAL BODIES

In the early years of planetary exploration, the sequence of missions was controlled much more by technical feasibility than by scientific priority. Any mission would increase our knowledge greatly, as so little was known. However, we now face a different situation. There is a significant, albeit uneven, distribution of data about the inner planets (Table 1). Reconnaissance of the terrestrial planets and the Galilean satellites, if defined to include at least a spacecraft flyby of these objects, will be completed by 1980. Only asteroids and comets will lack close observation, although observations of the surface of Venus are still sparse.

With the existing data, comparative study of the planets has become a significant scientific endeavor. The greatest advances in understanding of the origin and evolution of the planets and of properties of the solar system will come from studies of the suite of terrestrial bodies rather than from studies of a single planet. Common features such as atmospheres, magnetic fields, and various geologic processes can best be understood by such comparative techniques. Knowledge of the planet Earth is important as a reference, and comparative planetary studies provide insight about the history and evolution of the Earth. Missions to the Moon and Mars showed that each was interesting and unique. Planets are not duplicates but individuals. At the same time, data from these bodies help define the early history and processes of the solar system that affected all bodies.

An important aspect of the comparative study relates to the origin and evolution of life. Has the Earth provided a unique environment for evolving and supporting life? Did other bodies of the solar system ever have life? Although the Viking mission to Mars addressed this question, more studies are needed before a convincing answer can be found.

Another important consideration for the exploration of the terrestrial bodies in the 1980's is the assessment of their potential for utilization as space resources. In a period when natural resources are being depleted rapidly on the Earth, no detailed assessment has been made of the resources that exist in space. It is felt that the Moon and asteroids may hold particular potential as sources of metals and minerals for space industrialization and utilization. The initial utilization of such resources may be to support space missions.

In summary, the overall science objectives that must guide the exploration strategy in the 1980-1990 period include:

- (1) Obtaining basic knowledge about the terrestrial bodies-- their form and surface features, their composition, internal structure and dynamics, the structure, composition

Table 1. USA Terrestrial Bodies Exploration

Planet	Flyby	Orbiter	Lander
Mercury	1 (Mariner 10)	0	0
Venus	3 (Mariners 2, 5, 10)	0	0
Moon	3 (Rangers 7, 8, 9) ^a	5 Lunar Orbiters 8 Apollo CSM ^b 2 Apollo Subsatellites ^b	5 (Surveyors 1, 3, 5, 6, 7) 6 Apollo Lunar Modules ^b
Mars	3 (Mariners 4, 6, 7)	3 (Mariner 9, Vikings 1, 2)	2 (Viking 1, 2)
Asteroids	0	0	0
Galilean Satellites	2 (Pioneers 10, 11) ^b	0	0
Comets	0	0	0
Expected by 1980			
Venus		1 (Pioneer Venus 4 Probes) ^b	
Galilean satellites	2 (Voyagers 1, 2)		
^a Approach studies prior to collision.			
^b Extremely low resolution observations.			

and dynamics of their atmospheres, and properties and histories of their magnetic fields. These are basic elements necessary for understanding the planets and solar system.

- (2) Comparative studies and understanding of common planetary processes such as interactions of magnetic fields and atmospheres with solar wind, dynamical meteorology, climatic variation, thermal evolution and planetary differentiation, volcanism, plate tectonics, and other geologic processes.

Understanding the Earth, its history and its future, is an important part of this objective.

- (3) Determining the special conditions for the presence or evolution of life on terrestrial bodies.
- (4) Preliminary assessment of space resources.

Thus the goals must be set and an exploration strategy planned to achieve these objectives.

SECTION III

EXPLORATION STRATEGY AND RECOMMENDED MISSION PLAN

In the period 1980-1990, it is essential for economic and scientific reasons that the goals of the exploration of the terrestrial bodies be well defined. At present there is an uneven distribution of data on different bodies. Little is known about comets, asteroids, the Galilean satellites, and the surface of Venus, but the Moon and Mars have been explored in some detail. This has come about as a result of the combined effects of science priorities and technological capabilities. Anticipated technological advances within the coming decade will make it possible to launch productive scientific missions to many of the terrestrial bodies.

The general goals of the exploration in the 1980's include:

- (1) Completion of the reconnaissance of those bodies that have not yet been explored by spacecraft: asteroids and comets.
- (2) Further exploration of Mercury and of the Galilean satellites.
- (3) Intensive study of the Earth's close neighbors: the Moon, Mars, and Venus.

The exploration strategy to achieve these goals must be a coherent program with a logical sequence of missions guided by science objectives, launch opportunities, the availability and orderly development of required technology and theoretical frameworks for optimum science return, and incorporation of science input from previous missions and from Earth-based or Earth-orbit-based observations.

Figure 1 presents the recommended mission plan of the Terrestrial Bodies Science Working Group. The plan spans the 10-year period 1981 through 1990, indicating launch years and periods of operational activity.

The series of missions proposed here is a reasonable and coherent program of reconnaissance, exploration, and/or intensive study of the terrestrial bodies. It is recognized that missions proposed within any given time frame may be competitive in a fiscal sense; however, they are not competitive scientifically. Each mission to a given body builds upon available knowledge and each will provide new data of primary scientific import. Thus, we recommend that if fiscal constraints prohibit initiation of one or more of these missions within any given year, the mission(s) in question be proposed again, repeatedly if necessary, in the subsequent year(s), provided launch opportunities are available. Each of the proposed missions is worthy; each will contribute significantly toward increased understanding of the terrestrial bodies.

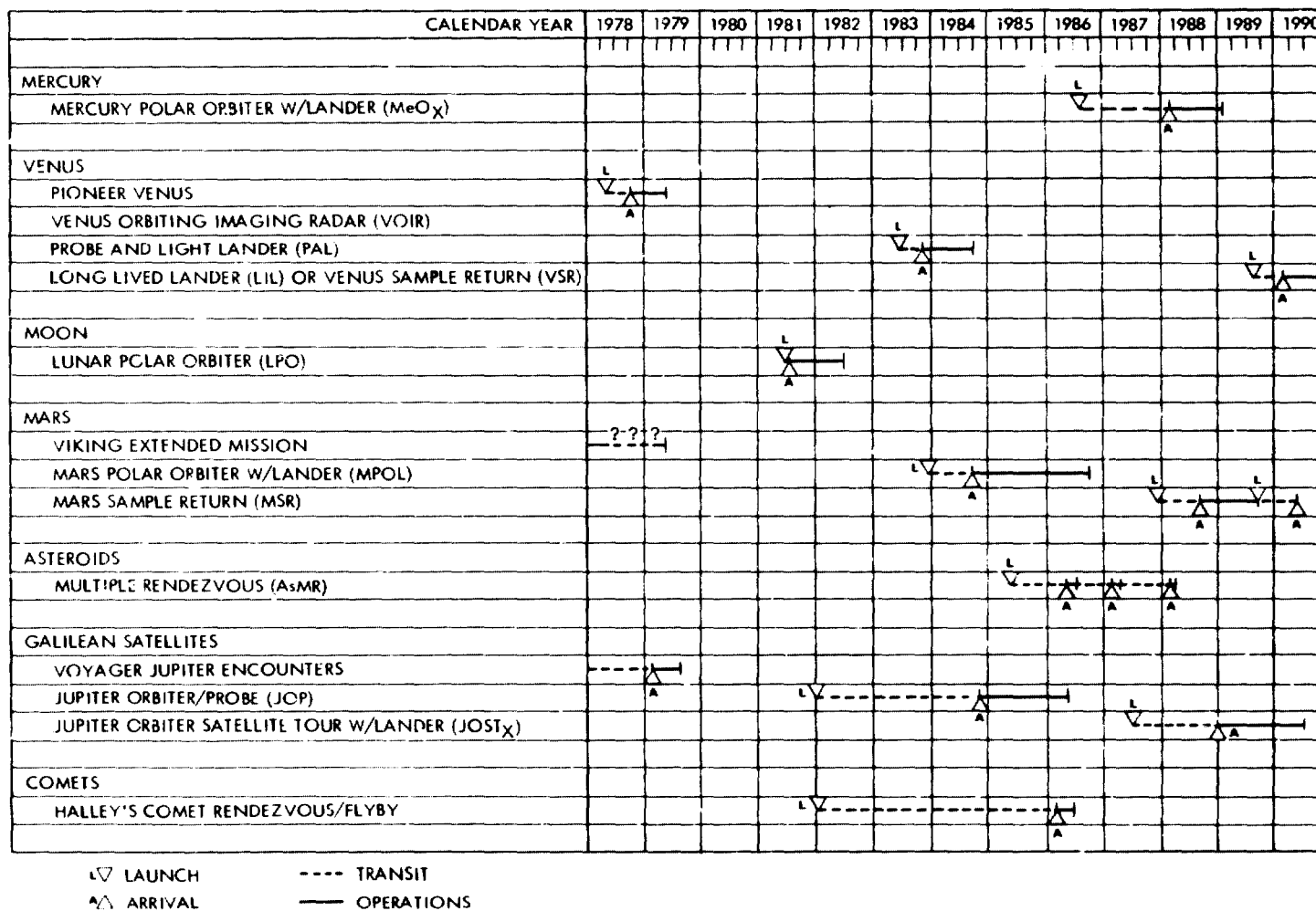


Figure 1. TBSWG Recommended Mission Plan for 1980-1990

Each mission we have shown in Figure 1 complements the total ensemble of programs. Each mission is designated by a triangle indicating launch, a dashed line indicating transit periods, and a solid line marking the period of nominal mission operations. Most of the missions require about three years between project start and launch. The Lunar Polar Orbiter (LPO) may only require a 2-year lead time owing to its advanced state of planning. Because of greater complexity, the Mars Polar Orbiter-Lander (MPOL) will probably require four or five years lead time and Mars Surface Sample Return (MSSR) will probably require at least six years lead time. Several missions are scheduled later in the decade because they will benefit greatly by development of low-thrust propulsion.

A single mission is recommended to address objectives at Mercury. Either a 1986 mission utilizing solar-low-thrust propulsion or a 1986 ballistic mission are recommended. The spacecraft should consist of a polar orbiter with geochemical, geophysical, and geological instrumentation and a subsatellite and/or surface lander (MeOx).

For Venus, a program of three missions is proposed: (1) a Venus Orbiting Imaging Radar mission in 1983 (VOIR), (2) a probe and short-lived lander mission in 1986 (PAL), and (3) a long-lived lander or Venus surface sample return mission in 1989 (LIL or VSSR). The mission configuration of PAL depends on USSR and US Venus exploration progress, while that of LIL depends mostly on technological developments, such as high-temperature instrumentation.

Lunar exploration should be renewed after a 10-year dormancy with the proposed Lunar Polar Orbiter (LPO) global survey mission. This mission is considered of high priority as the first in the overall program of terrestrial body geoscience orbiters, paving the way for similar missions to other planets. Initiation of post-LPO lunar exploration will depend critically upon renewed interest in manned exploration or human resource utilization.

A two-mission program is recommended for Mars. In 1984, a Mars Polar Orbiter with lander (MPOL) should consist of a geoscience orbiter and some form of lander system. Penetrators, hard landers, and rovers are candidate vehicles. The lander option must be evaluated on its capabilities to achieve the network science and detailed study goals outlined in a later section.

In 1988, a Mars Surface Sample Return (MSSR) with mobility represents a culmination of the extensive program of Mars exploration. Sampler mobility, necessary to collect well chosen samples, is considered of vital importance; the nature of this mobility (advanced sampler arm, tethered rover, or full vehicle mobility) must be carefully studied to optimize sample selection.

A single mission to the asteroids (AsMR) will provide a reconnaissance of these bodies by encounters with several different types of asteroids. Extensive study of trajectory opportunities is needed before a specific mission can be chosen. However, the time period 1984-1986 is recommended as providing a proper treatment of the asteroids within the overall terrestrial bodies strategy.

The Galilean satellites represent an important arena for future exploration, and this importance is reflected in the recommendation for two missions. The first is a refined version of the Jupiter Orbiter/Probe mission, redefined with a mission profile planned to enhance satellite science and many satellite encounters. A satellite-intensive Jupiter Orbiter Satellite Tour (JOSTx), including a lander (for deployment on one or more of the satellites), should be flown in the late 80's.

Finally, a Halley's comet rendezvous (HCRV) is considered the premier comet mission of the 1980's. To achieve a true rendezvous mission will require development of a low-thrust propulsion system (solar sail or ion drive). Even if such a system is not developed, a Halley's comet flyby is recommended in the mid 80's, as any study of Halley's comet will provide the best opportunity to address the fundamental questions of cometary science. Summaries of the exploration plans for the individual bodies are given in the following sections.

SECTION IV

SUMMARY OF EXPLORATION PLANS

A. EXPLORATION OF MERCURY

Our present knowledge of Mercury, based primarily upon astronomical observations and the Mariner 10 mission, is not as advanced as that for Mars, the Moon and Earth. Mercury is a small body with a radius of 2440 km. It is dense (mean density $\bar{\rho} = 5.44 \text{ gm/cc}$), and has a heavily cratered, Moonlike surface. It is inferred to have an iron core with a diameter about three-fourths that of the planet. It has a weak global dipole magnetic field ($\sim 4 \times 10^{-4}$ times that of Earth) which is oriented close to the axis of rotation. Mercury is the planet closest to the Sun, to which it is locked in a $3/2$ spin-orbit resonance. It has no atmosphere ($< 10^{-8} \text{ mb}$) and is inferred to have a crustal and bombardment history much like that of the Moon.

Increased understanding of Mercury and measurements in its environs will contribute to increased understanding in several major science phenomena including the following: condensation as a function of position in the nebula during formation of the solar system; thermal evolution of small, dense bodies in the solar system; bombardment chronologies as a function of position in the solar system; origin of planetary magnetic fields; solar neutron production, and non-Newtonian, metric gravitational theories.

Mercury science objectives can be addressed by a polar orbiter with geochemical, geophysical and geologic instrumentation, augmented with several mission-peculiar instruments (e.g., UV spectrometer, solar neutron detector, neutral mass spectrometer). Science objectives would be best met by placing this large science payload in a circular, low-altitude ($\leq 500 \text{ km}$) orbit. Propulsion and thermal requirements make it desirable to use a low-thrust propulsion system such as solar sail or ion drive to meet the science objectives. A small lander and/or a subsatellite would significantly augment the science return, especially in helping to answer the prime question of the internal structure of Mercury. A 1986 mission (MeOx) using low-thrust propulsion would provide a circular orbit with sufficient mass margin for good orbital science, for thermal control, and for a simple lander and/or subsatellite. A similar mission could be launched ballistically in July 1986, but would have a long flight time and a somewhat lighter payload.

B. EXPLORATION OF VENUS

Venus, although similar to Earth in size and location, is by far the least explored and the least understood terrestrial planet. This lack of knowledge will persist even after the Pioneer Venus mission and after any anticipated USSR Venera missions in the near future. For this reason, many of the immediate goals for the exploration of Venus represent a "catch-up" phase and it is imperative that this phase be completed as soon as possible. At stake is not just our

basic understanding of the planet itself but our ability to make meaningful comparisons of Venus with its neighbors, especially the Earth.

After Pioneer Venus there will remain many important questions about Venus. Concerning the Venusian surface we need to know the global morphology, including distribution of physiographic regions such as highlands and basins; the presence or absence of volcanic land forms, impact features, tectonic features, and aeolian depositional and erosional forms; the types of rocks and their elemental and mineralogical compositions, isotopic, and trace-element abundances; and the surface chemistry. We must learn about the structure, the existence, composition, physical state, and size of core, mantle, and lithosphere; the thermal structure, including distribution of radioactive heat sources; the extent of tectonic activity; and magnetic field generation. About the atmosphere we need more information on dynamics, including definition of global wind patterns, driving mechanisms, momentum and energy transport processes, characterization and identification of planetary waves, intensity and distribution of turbulence; the structure, particularly in the altitude range 65-135 km, and subpolar and polar regions; the composition between 65 and 135 km, including the vertical distribution of a dozen molecular constituents; and the chemistry of the atmosphere. The clouds are a major feature of Venus. We need to determine the composition by direct sampling, their particle sizes, numbers, and distribution including solid particulates; their optical and thermal properties; and the processes of particle nucleation, growth, and evaporation. Finally, there remain important questions on the origin and evolution: growth from the nebula, thermal history (including core and crust differentiations), and volatile evolution. A recommended sequence of missions which would logically address most of the science questions is as follows:

(1) Venus Orbiting Imaging Radar (VOIR)

The primary purpose of this mission to be launched in 1983 is global radar imaging of the surface at a resolution better than 1 km, with selected areas at a resolution of less than 100 m. Additional important goals include (a) gravity field determination, (b) atmospheric compositional analysis between 65 and 135 km, (c) cloud imaging, (d) temperature sounding, with (e) coordination between US orbiter experiments and landed USSR experiments.

(2) Venus Short-Lived Lander and Probe/Balloon (PAL)

The primary purpose of this mission in 1986 is geochemical analysis and investigation of the surface at multiple sites. Additional important goals include (a) atmospheric measurements from either advanced probe or balloon platform and (b) surface imaging.

- (3) 1989 Venus Long-Lived Lander (LIL) or Venus Surface Sample Return (VSSR)

A choice between these two missions should be made in 1984 on the basis of technological developments plus scientific results from earlier missions. The primary purpose of LIL would be the determination of the interior structure. Additional important goals are (a) surface composition and (b) atmospheric character. The primary purpose of a Venus surface sample return would be detailed trace element and isotopic analyses, leading to greater understanding of crustal evolution, surface-atmosphere interactions, radio-chronology, and other details of Venus history.

C. EXPLORATION OF THE MOON

In the context of exploration of solid bodies, one crucial data set for the Moon is still lacking, namely, the global geochemical and geophysical survey, as proposed for the Lunar Polar Orbiter (LPO). The LPO mission, first in a series of survey orbiters to solid bodies, has our strong endorsement for an early new start. The expected data from that mission are needed now to constrain and guide developing theories of the nature of the Moon. Interpretation of LPO data will be enhanced by the knowledge we are obtaining from Apollo samples and data. Interpretation of global data for other planets (e.g., those expected from Mars and Mercury in the 1980's) would benefit strongly from our experience with LPO data. Data for the Moon are vital to this program because the Moon is close to the Earth, has no atmosphere, and has a well-established chronology for its early differentiation and volcanism. LPO data also constitute a global resource survey essential to preparing for manned or unmanned lunar bases and utilization of lunar resources. We expect there will be lunar bases or detailed plans for such bases by the end of the 1980's. Thus, we urge that the LPO mission be flown in the early 1980's. Our recommended program for continued lunar exploration in the 1980's is as follows:

- (1) Continue analysis of Apollo and Luna samples and data, both to improve our understanding of the Moon and to maintain a group of planetary scientists with abundant lunar experience and interest.
- (2) Carry out the global geochemical and geophysical survey (LPO) as soon as possible.
- (3) Site characterization for lunar bases in the late 1980's may instigate missions using hard landers, soft landers, and automated sample return to provide geologic engineering and resource characterization and to make extensive local geologic, geochemical, and geophysical studies as an advanced step in planetary exploration.

D. EXPLORATION OF MARS

Mars is a complex planet; it has a heterogeneous surface and is geologically, meteorologically, and chemically active. Increased knowledge of Mars, of its origin, evolution and current status and of the nature of any extant Martian biota, has obvious bearing on our understanding of the present nature and past development of the Earth and of life.

Planet-wide imaging of Mars has provided definition of diverse terrains on a planetary scale and a relative chronology of surface evolution. The presence of extensive volcanism indicates that the planet is chemically differentiated. Surface materials are apparently strongly oxidized and chemically reactive. Detailed investigations indicate that the atmosphere has evolved in composition; a relatively dense atmosphere may have existed in the past. The atmosphere interacts with the surface in several ways: by interchange with solids at the poles, by chemical oxidation and transport in surface materials, and by entrapment as permafrost or by adsorption in the Martian regolith. Morphological features suggest that water once flowed on the surface. Evidence of plate tectonics has not been found, but like Earth, Mars exhibits at least one region that is not gravitationally compensated. These observations suggest that Mars is intermediate in evolutionary complexity between the Moon and Earth. Mars can provide data essential to understanding the processes that formed Earth's mantle, crust, and early atmosphere.

To answer the range of questions that can now be posed about Mars requires four approaches:

- (1) Whole-planet mapping: Comprehensive mapping of the surface morphological, lithological and chemical provinces of the planet, its gravity, magnetic fields, atmosphere, and other whole body properties using orbiting spacecraft. These data are part of the basic set required for comparative planetology; they provide the context for surface measurements and allow their extrapolation to answer planetwide questions.
- (2) Network science: Geophysical measurements (e.g., seismic study of interior structure, heat flow to define the thermal state, and meteorological stations) require the establishment of a network of stations that operate over an extended period of time. It presently appears that such a network can best be emplaced by penetrators or rough landers.
- (3) Surface science: Detailed investigations at the Martian surface on the interaction of the surface and atmosphere, detailed properties of surface materials, stratigraphic investigations of depositional history, atmospheric composition and evolution, and biological questions. These data supplement that obtainable from returned samples by providing information on additional localities and can provide surface data for correlation with orbital mapping.

- (4) **Sample analysis:** Sample return for analysis on Earth represents the best way to obtain many types of petrological, chemical, isotopic, biological and physical data for Mars. The return of unsterilized Martian materials can uniquely provide data on the absolute chronology of Martian rock units, on detailed detection and characterization of Martian life, on surface-atmosphere interaction processes and rates, and on the composition and evolution of Mars' crust and mantle. A sample return must provide rationally chosen samples from carefully selected areas (using limited mobility).

Data from all of the above approaches must be synthesized to answer planetological questions. Opportunities to combine the objectives in single missions should be studied carefully. We recommend three programs for exploration of Mars through the 1980's.

- (1) **The Viking Extended Mission:** The four spacecraft currently deployed should be used to the fullest possible extent, and the data obtained must be vigorously analyzed to provide maximum information. One or two Martian years of observations will cover seasonal and spatial variations of dust storms, atmospheric conditions and surface features. Adequate support must be provided for both the extended mission and for continued data analysis and synthesis.
- (2) **Global-environmental mission (MPOL):** This mission, to be launched in the 1984 opportunity, would consist of an orbital science package capable of whole-planet coverage, a penetrator or rough lander network (6-12 vehicles) for geophysical and geochemical studies, and soft landed stations (including surface mobility) to extend the surface investigations done by Viking. Such a mission would provide unique planetary global and environmental data and would prepare for subsequent sample return missions.
- (3) **Mars Surface Sample Return (MSSR):** Sample return should be a principal long-term objective of Mars exploration. A mission launched in the 1988 opportunity will permit the application of the powerful tools available in earth-based laboratories to investigate both the planetological and biological history of Mars. Positive results from such studies may warrant continued, intensified investigations during the following decade.

Both of the future Mars missions recommended here (MPOL and MSSR) require immediate study and development efforts in order to make the most efficient and intelligent use of flight opportunities. A large number of systems and instruments must be developed, but an even longer lead time is required for planning and design of a system for containment and monitoring of samples and for definition, building, and testing of the sample receiving laboratory and of quarantine protocols.

E. EXPLORATION OF THE ASTEROIDS

The asteroids have high potential for elucidating conditions that existed during the first half-billion years of the solar system's existence. The "reconnaissance phase" of asteroid exploration has included ground-based astronomical measurements, laboratory analyses of presumed asteroidal fragments (the meteorites), and theoretical investigations. No spacecraft mission has yet addressed these bodies.

Future exploration of the asteroids should be geared to the following major objectives: establishing genetic relationships among mainbelt asteroids, Apollo-Amor asteroids, Trojans, comets, planetary satellites, meteorites and interplanetary and interstellar dust; establishing the variation of nebular condensate composition as a function of position in the early solar system and the degree of subsequent mixing of these materials; understanding the physical processes of accretion and fragmentation and why an asteroidal planet failed to form; understanding the thermal evolution of various asteroids and establishing the source(s) and time scale(s) of the heating process(es); establishing the degree to which asteroidal fragmentation gave rise to cratering episodes on the terrestrial planets and determining cratering chronologies; and evaluating the potential of the asteroids as sources of raw materials for economic utilization.

Because of the interrelated manner in which these highly heterogeneous bodies provide useful clues concerning the above questions, we recommend that an asteroid program explore representatives of several major compositional types of asteroids, plus a few unique asteroids such as Vesta. Essential measurements include mass-determination, elemental chemistry, imaging, magnetometry, and multispectral mapping at moderate spatial resolution. We find that several of these goals (especially chemistry) require long stay-times, hence very low encounter velocities. Thus a good asteroid mission must encounter a number of selected asteroids and have rendezvous capability at several of them.

TBSWG recommends a multiple-asteroid rendezvous mission (AsMR) for the mid-1980's, following the development of a suitable low-thrust propulsion device (e.g., solar sail or ion drive). There are numerous multi-asteroid opportunities available in any given year. It is important that a complete search for trajectories be made to determine the best sequence of encounter for the AsMR mission.

Specific recommendations for the study of asteroids and meteorites are:

- (1) A multi-asteroid rendezvous mission should be flown in the 1985 time frame. Advanced mission studies should begin now for an orderly development of this mission.
- (2) A vigorous ground-based program of asteroid observation must be continued, using optical, thermal IR, and radar techniques.

- (3) A broad program of meteorite research should continue in order to capitalize on the experimental techniques perfected in lunar sample analysis by applying them to the wide variety of extraterrestrial samples in meteorite collections.
- (4) A sustained theoretical effort should be supported to understand the processes that affected the asteroids and meteorite parent-bodies and to relate them to questions concerning solar system origin and planetary evolution.

F. EXPLORATION OF THE GALILEAN SATELLITES

The study of the origin and evolution of the solar system centers about understanding early processes that produced differences in bulk composition among planetary objects and why different planetary bodies evolved along different paths. In several ways Jupiter and the four Galilean satellites resemble a miniature solar system, the study of which can be expected to yield profound insights into both aspects of planetary history.

Recent studies suggest that Jupiter was once a central heat source with a luminosity perhaps 1/100 that of the present Sun. Thus, heating from Jupiter may have produced the differences in composition and density among the Galilean satellites, which are even greater than those among the terrestrial planets. Densities range from 3.5 g/cm³ for Io, a rocky object, to 1.7 g/cm³ for Callisto, whose interior is dominantly H₂O.

Moreover, these four planets (Ganymede and Callisto are the size of Mercury, Io and Europa are the size of the Moon) are likely to be highly differentiated. It is believed that Ganymede and Callisto have Moon-sized rocky cores overlain by liquid water mantles hundreds of kilometers thick that are capped by icy-rocky crusts. These four objects also appear to have evolved upon four different evolutionary paths, with the result that their surfaces appear very different. Current speculation is that the surface composition is as follows: Callisto - carbonaceous/organic material mixed with very little H₂O ice; Ganymede - a higher proportion of H₂O ice, less carbonaceous material and unidentified constituents; Europa - mainly H₂O ice with small amounts of rocky and coloring material (e.g., S); Io - little or no ice, mainly sulphur and sulphur compounds, including salts. The implied former presence of water on Io's surface is particularly intriguing in light of the suggestion that early Jupiter was supplying as much energy to Io's initial surface as the Sun now supplies to the Earth. Each surface is also known to exhibit regional patchiness suggesting the existence of varied geochemical geologic provinces. Finally, the interaction of Io with Jovian magnetospheric particles is one of the solar system's most striking examples of the interaction of a planetary object with its space environment.

These objects are important targets for exploration in the 1980's. Therefore, we make the following recommendations:

- (1) The satellite science portion of the 1981 Jupiter Orbiter (JOP) mission should be augmented by choosing an orbit with numerous satellite encounters. The possibility of using a second JOP spacecraft in 1983 as a cost-effective means for exploring the system should be seriously considered.
- (2) A satellite-intensive Jupiter Orbiter Satellite Tour (JOSTx), including a lander for one or more of the satellites, should be flown in the late 1980's. Orbiter payloads should include:
 - (a) Visible and infrared imaging and spectrometers for studies of the satellite surfaces, processes, and lithologies.
 - (b) An ultraviolet spectrometer for satellite atmospheric studies.
 - (c) An experiment to measure the abundance and distribution of chemical elements on the satellite surfaces.
 - (d) An ion mass spectrometer and magnetometer for study of particles and fields.
 - (e) Mass/gravity studies afforded by tracking data.
 - (f) Atmospheric radio occultation measurements.
- (3) The JOSTx lander would offer our first close look at an icy body and our first scientific base in the outer solar system. It could provide close-up multispectral imaging, seismic studies, atmospheric studies, near-surface fields and particles studies, surface chemical analysis, and synoptic observations of the satellites and Jupiter.

G. EXPLORATION OF COMETS

Comets are the least understood of all the solid objects of the solar system. The nature of these objects, with atmospheres larger than the Sun and tails some 1 AU in length, is one of the most fascinating puzzles of the solar system. Cometary nuclei may be the most primitive unaltered debris left over from the solar nebula; hence, an understanding of the structure and composition of cometary nuclei could provide valuable clues to the origin of the solar system.

Confirmation of the existence and determination of the geometry of the nucleus by direct imaging, of dust composition, of density of atomic and molecular species and their motions, of magnetic fields, and of plasma waves are facets of a scientific program that could provide a quantum leap in our understanding of comets. A rendezvous mission will allow more detailed studies of these problems than would

a flyby mission. The decade of the 1980's provides us with the opportunity to study the only very large and predictable comet--Halley's comet--in 1985/86. This unique opportunity must not be allowed to slip by.

Therefore, we recommend a solar sail or ion drive mission to Halley's comet, launched in 1982 to rendezvous with the comet before or near perihelion in 1986.

The main technological difficulty in this mission is the timely development of the solar sail or ion drive. Because of this uncertainty, other alternatives should be considered. These include:

- (1) A solar sail or ion drive mission to Halley's comet, with a later launch than for rendezvous for a slow flyby.
- (2) A ballistic mission to Halley's comet.
- (3) A ballistic mission to other comets such as Giacobini-Zinner and Borrelly.

SECTION V

PROGRAM SUPPORT RECOMMENDATIONS

The TBSWG has reviewed the existing and potential capabilities for solar system exploration, the lead time necessary for space missions, and the history of past missions. This review indicates once again that stronger emphasis must be given to the conception and early development of a wide spectrum of experiments, instruments, and vehicles in order to derive the proper return from an exploration program. An augmented program of analysis of existing data, laboratory and theoretical studies, and Earth-based and Earth-orbital observations is also required to build on past missions toward the logical and efficient exploration of the solar system.

TBSWG feels that cost-effective science in the 1980-1990 decade can only be obtained by the adoption of both the coherent mission plan described in the previous section and well-planned support of complementary research and development as summarized in the following sections and detailed in Volume IX of this report.

A. SUPPORTING RESEARCH AND TECHNOLOGY PROGRAM

Adequate SRT support must be provided for the following key technical developments:

- (1) Delivery systems:
 - (a) IUS for planetary missions.
 - (b) Low-thrust propulsion (solar sail-ion drive).
- (2) Spacecraft:
 - (a) Thermal shields (Mercury).
 - (b) Stabilized platforms.
 - (c) Orbital and entry science instruments.
- (3) Surface landers and instrumentation:
 - (a) Penetrator/rough lander.
 - (b) Soft lander.
 - (c) Rover.
 - (d) Surface science instruments.
- (4) Sample return capability and receiving lab: containment, quarantine, and contingency sterilization tests.

- (5) High temperature technology (Mercury-Venus).
- (6) Radiation hardening (Galilean satellites).
- (7) Spacecraft communication, signal processing, and tracking.
- (8) Earth-based and Earth-orbital observation instruments.

We find that support for technological development is far too closely tied to support for individual missions. At the present time many of the candidate instruments for a Mars lander have had little development support. The mission plan recommended in Figure 1 will require support in key technological areas and instruments. It is recommended that "SR&T planning" be formally carried as an advanced planning item on an equal basis with various mission plans by the advanced planning group of the Lunar and Planetary Program Office and that developmental needs be announced by some form of Announcement of Opportunity on an annual basis.

B. EARTH-BASED AND EARTH-ORBITAL STUDIES OF THE TERRESTRIAL PLANETS

The spacecraft used in planetary encounters in deep-space missions should be devoted to critical observations that are not possible from ground-based or Earth-orbital observing platforms. Thus we recommend an active program using Earth-based and Earth orbital-based systems for planetary observations to complement and aid flight missions. Such a program should include increased support for new instrument development, observatory operation, ground-based telescopic studies, and balloon- and aircraft-based studies.

Further, we strongly recommend that a significant portion of space telescope schedules be made available for planetary studies and that NASA support development of instruments for these telescopes that are oriented toward planetary studies.

C. DATA ANALYSIS AND SYNTHESIS PROGRAM

To be cost-effective, planetary science must derive maximum return from each mission. This requires an orderly sequence of missions so that technical development, data, and increased understanding from one mission are used effectively in all subsequent missions. In addition, it requires effective planning and use of DA&S funding. Durations of missions and data analyses should be determined on the basis of science return rather than by arbitrary fiscal deadlines. Continued data synthesis support is an effective way of maximizing science return. Laboratory or theoretical studies may be absolutely critical to understanding mission observations. An adequate DA&S program will help to maintain a viable community of active planetary scientists during gaps between missions. We recommend that:

- (1) Most data analysis, data synthesis, experimental, and theoretical studies be supported from programs that are

not mission-associated so as to assure effective accomplishment of the goals and to enhance objectivity by reduction of the projects' dependence upon the goals of a particular mission. All such studies should be subject to peer review to broaden the judgment of input and to stimulate competitive attitudes.

- (2) Planning for planetary missions provide for economical support of extended low-level operation, subject to scientific review, because of the increased need for monitoring transient events.

D. EXTRATERRESTRIAL MATERIALS ANALYSIS

A strong program of analysis of extraterrestrial materials (lunar samples and meteorites) should continue through the 1980's. New information from such analyses (e.g., time scales, planetary differentiation processes) is essential to advancing planetary science. Equally essential are the continued interest and contributions of scientists whose backgrounds and research are directed toward laboratory analysis. Laboratories must be kept at state of the art in anticipation of new sample acquisitions as well as for improved study of materials on hand. Lunar samples and meteorites must be properly preserved and made available for study. Preparation must be made in a timely manner for receiving and curating new materials (e.g., Martian surface samples). Scientists with experience in studying lunar materials are needed for planning for lunar bases and resource utilization and missions for surface analysis and sample returns.

E. BROADENING SCIENCE SUPPORT BASE

The science investigations of planetary missions have been organized primarily by science teams consisting of principal investigators and their co-investigators. Eventually, science data are archived and distributed through a National Data Center. Results are published as reports and as articles in the open literature. However, during the most exciting times of the missions only the science team members have access to data.

Each planetary mission is a major national project. It is important that a broad segment of the interested scientific community share the excitement and first-hand results of planetary missions, while still maintaining the proprietary rights of the science investigators.

We make three recommendations to broaden scientific participation:

- (1) The material being released by the Public Affairs Office should be displayed, at about the same time, in a number of geographic locations. National data centers, science museums, or libraries could be utilized for this purpose. Interested scientists could see real photographs, data,

and accompanying descriptive material rather than the highly abbreviated versions of these that appear in the news media.

- (2) A timely archiving of data for distribution must be complemented by funds under data analysis and synthesis programs to enable interested scientists to participate in a timely manner in the analysis of the data.
- (3) Guest investigator programs for the major missions should be expanded.

F. INTERNATIONAL COOPERATION

Owing to the complexity, cost, and past indications of interest, a new initiative should be engendered in the case of the Venus lander mission in 1986 (PAL) and the Mars Surface Sample Return mission in 1988 (MSSR). The continuing active Soviet Venus program may make it possible to fly US surface experiments on a USSR Venus lander. Similarly, it may be possible to assign a particular segment of the Mars sample return mission to the Soviets.

It would be prudent to continue planning to carry out these missions alone, as they are essential parts of the planned exploration program. However, if the cost can be shared, then other missions may be feasible that might have to be deleted because of cost considerations.

That cooperation is possible has been demonstrated by the Apollo-Soyuz mission, by the exchange of lunar samples, and the exchange of data on Mars. The recent acquisition of the Luna 24 sample is a new indication that profitable negotiations might take place.

It has been pointed out that cooperative missions will take place only if they are of mutual benefit. The two missions cited above, we believe, meet this criterion. In addition, it may be possible to secure support from the European Space Agency and other nations for missions shown in the matrix once the Space Lab effort is completed.

SECTION VI

SUMMARY OF RECOMMENDATIONS

The TBSWG considered the objectives for the exploration of Mercury, Venus, the Moon, Mars, asteroids, Galilean satellites and comets. The group as a whole, and in panels, reviewed current knowledge, existing programs and approved missions. Then, taking into account the science goals, technological requirements and launch opportunities, it identified a series of missions for the period 1981-1990. The major recommendations of the Group for the exploration of the terrestrial bodies of the solar system are:

- (1) The goals of the terrestrial bodies exploration program in the 1980's should include: reconnaissance of the asteroids and comets, exploration of Mercury and the Galilean satellites, and intensive study of the Earth's closest neighbors--Mars, Venus and the Moon.
- (2) The exploration strategy must be a coherent program with a logical sequence of missions consistent with science goals and technological requirements. Specifically, exploration of the Moon, Venus, Mars, Jupiter and the comets should be initiated early in the decade of the 1980's and asteroids and Mercury should be considered as targets of exploration towards the middle of the decade. If fiscal constraints prohibit initiation of one or more of the missions of this strategy within any given year, the mission(s) in question should be proposed again, repeatedly if necessary, in subsequent years, provided suitable launch opportunities are available.
- (3) We recommend the following missions to individual terrestrial bodies:
 - (a) A single polar orbiter (perhaps including a landing vehicle) to address the planet Mercury in 1986.
 - (b) A three-mission program for Venus, including a radar mapping spacecraft (VOIR) in 1983, a probe and short-lived lander in 1986, and either a long-lived lander or sample return mission in 1989 or later.
 - (c) A lunar polar orbiter as early as possible, to provide vital data for synthesis with Apollo observations and as a precursor to other terrestrial planet orbiters.
 - (d) A two-mission Mars program, consisting of a 1984 Mars polar orbiter with lander(s) and a sample return in 1988.

- (e) A single asteroid-rendezvous mission to at least three different types of asteroids in the 1984-1986 time frame.
 - (f) A Jupiter orbiter satellite tour with satellite lander in the late 1980's to follow the Jupiter Orbiter/Probe mission with satellite intensive observations (1982).
 - (g) A rendezvous flyby of Halley's comet in 1982.
- (4) In addition to these mission recommendations, there are nonmission program issues necessary to optimize the science return. We recommend:
- (a) Adequate SR&T funds to support technologies for advanced spacecraft and delivery systems and instrumentation.
 - (b) That SR&T be carried as a formal planning item, comparable to individual spacecraft missions, with an annual Announcement of Opportunity.
 - (c) Support for Earth-based and Earth-orbital planetary observations, including instrument development and access to space telescopes.
 - (d) That a rigorous data analysis and synthesis (including experimental and theoretical studies) independent of specific missions be carried as an important, ongoing research program.
 - (e) A strong program in extraterrestrial materials (lunar samples and meteorites) analysis and preparation for analyses of Martian or Venusian samples to be returned late in the decade.
- (5) We encourage efforts to broaden scientific participation in space sciences, both within the USA and abroad. We recommend:
- (a) Mechanisms to expedite the availability of new data to the scientific community.
 - (b) Guest investigators programs encouraging both domestic and foreign participation.
 - (c) International cooperation to study specific planets by coordinated investigations, exchange of spacecraft instrumentation and joint ventures.